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Frequency Agile Microwave Photonic Notch Filter in a Photonic Chip

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The primary objective is to explore a novel class microwave photonic (MWP) notch filter with a very narrow isolation bandwidth, an ultrahigh stopband rejection, a wide frequency tuning, and flexible bandwidth reconfigurability, integrated in a compact photonic chip.

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Electro-optic Modulator, Microwave photonic filter, Nanophotonic devices, Reconfigurable RF Notch Filter

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Frequency Agile Microwave Photonic Notch Filter in a Photonic Chip

Final Report **(performance period:**

1. **Problem statement:**
Interference mitigation is crucial in modern radiofrequency (RF) communications systems with dynamically changing operating frequencies, such as cognitive radios, modern military radar, and electronic warfare (EW) systems. To protect sensitive RF receivers in these systems, frequency agile RF filters that can remove interferers or jammers with large variations in frequency, power, and bandwidth are critically sought for. Unfortunately, an RF band-stop or notch filter that can simultaneously provide high resolution, high peak attenuation, large frequency tuning, and bandwidth reconfigurability does not presently exist. Microwave photonic (MWP) filters are capable of tens of gigahertz tuning and have advanced in terms of performance, but most are limited in stopband rejection due to the challenge in creating a high quality-factor optical resonance used as the optical filter. Thus, to achieve MWP filters with similar performance to state-of-the-art RF filters in terms of isolation bandwidth and rejection is still very challenging, especially in compact integrated photonic chip footprint.

2. **Program objective:**
The objective of this program is to achieve a novel class microwave photonic (MWP) notch filter with a very narrow isolation bandwidth, an ultrahigh stopband rejection, a wide frequency tuning, and flexible bandwidth reconfigurability, integrated in a compact photonic chip. Target values to achieve are: 1-40 GHz frequency tuning, 10-100 MHz bandwidth tuning, >60 dB peak suppression, and 0 dB passband insertion loss. The program will also deliver a prototype of the high performance filter with computer-control capability of reconfiguring the filter properties, such as center frequency, bandwidth, and suppression.

3. **Approach:**
The approach of the project to realize the high performance filter high performance is to exploit stimulated Brillouin scattering (SBS) in a photonic chip as optical filtering technology, combined with a new concept of RF sidebands amplitude and phase controls using an electro-optic modulator to enhance the filter suppression through frequency selective interference. The realization of this filter is explored in various fiber-based and photonic-chip based platforms, including chalcogenide, silicon, silicon nitride, and standard single-mode fiber. Utilization of the filter technology to another functionality, namely in an instantaneous frequency measurement (IFM) system was also explored.

4. **Results and discussions:**
   a. ***High extinction tunable notch filter in a chalcogenide chip*** **[Optica 2, 76 (2015)]**
   Here, we demonstrate experimentally a highly selective SBS integrated microwave photonic bandstop filter in a centimeter-scale chalcogenide glass waveguide that operates with a low

pump power (8–12 mW) and a low SBS gain (1–4 dB), while maintaining high, reconfigurable resolution (32–88 MHz) and high stopband rejection of >55 dB. We further show that the filter can be tuned over a wide frequency range of 0–30 GHz (Figure 1a), leading to a unique performance combination difficult to match with any existing filter technology. We achieved this performance through on-chip SBS filtering of a phase- and amplitude-tailored RF-modulated optical spectrum resulting in precise RF signal cancellation at a resolution comparable to state-of-the- art RF filters.

We further demonstrate the first high resolution RF filtering experiment using the chip-based MWP filter. We consider a scenario in which two RF signals, one of interest and the other an unwanted interferer separated in frequency by 20 MHz, were supplied to the input of the filter. We compare the output RF spectra from a conventional single-sideband MWP filter Figure 2(b, upper) As expected the unwanted tone power was reduced by 17 dB, but the signal attenuation was as high as 9 dB, which indicated that the conventional filter resolution was below 20 MHz. This clearly demonstrates the limitation of the conventional approach, which cannot simultaneously achieve high resolution and high-suppression filtering. In contrast, this can be achieved using on-chip SBS filter, as shown in Figure 2(b, lower). The measured interferer suppression in this case was 47 dB, limited by the noise floor of the measurements.

This paper is in the top 1% highly cited paper of the academic field of Physics according to Web of Science.

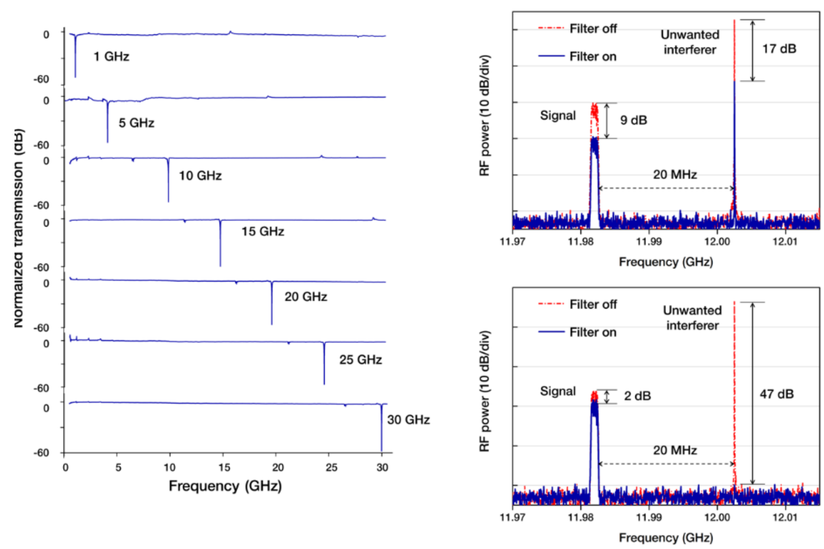

Figure 1. (a) 1-30 GHz frequency tuning of the on-chip SBS MWP filter. (b) High-resolution RF filtering experiment. Two RF signals with 20 MHz frequency separation were used at the filter input. (upper) Filtering with conventional single-sideband scheme with 17 dB SBS loss as optical filter. Peak attenuation at the unwanted interferer tone was 17 dB, and signal attenuation was 9 dB. (lower) Filtering with the cancellation filter using 4 dB of SBS gain. Complete reduction of unwanted interferer was observed with low attenuation of the desired signal (2 dB).

b. *Tunable SBS notch filter in a silicon chip* [Optics Letters 40, 4154 (2015)]

Microwave photonic filters based on SBS have shown excellent properties in terms of high resolution and extinction. Although efficiently generated in soft glasses such as chalcogenides, there is a strong demand to harness SBS in silicon, a material platform that supports large scale integration between photonics and electronics. Unfortunately, for the CMOS-compatible silicon-on-insulator (SOI) platform, SBS has been elusive. The low elastic mismatch between the silicon core and the silicon dioxide substrate result in weak acoustic confinement, preventing build-up of the SBS process. A recent breakthrough achieved forward propagating SBS (FSBS) in a silicon nanowire by partially releasing the nanowire from its substrate. However, the amount of SBS gain that was reported, including this geometrical enhancement and novel fabrication methodology, was limited to around 4 dB, which is hardly usable for conventional signal processing applications.

In this work, we report the first functional device for signal processing based on SBS from a silicon nanowire. We employ a novel cancellation filter technique to harness this modest SBS gain in silicon, creating a high-performance microwave photonic notch filter (Figure 2a). We use only 0.98 dB of on-chip SBS gain to create a cancellation microwave photonic notch filter with 48 dB of suppression, 98 MHz linewidth (Figure 2b), and 6 GHz frequency tuning (Figure 2c). This demonstration establishes the path toward monolithic integration of high-performance SBS microwave photonic filters in a CMOS-compatible platform such as SOI.

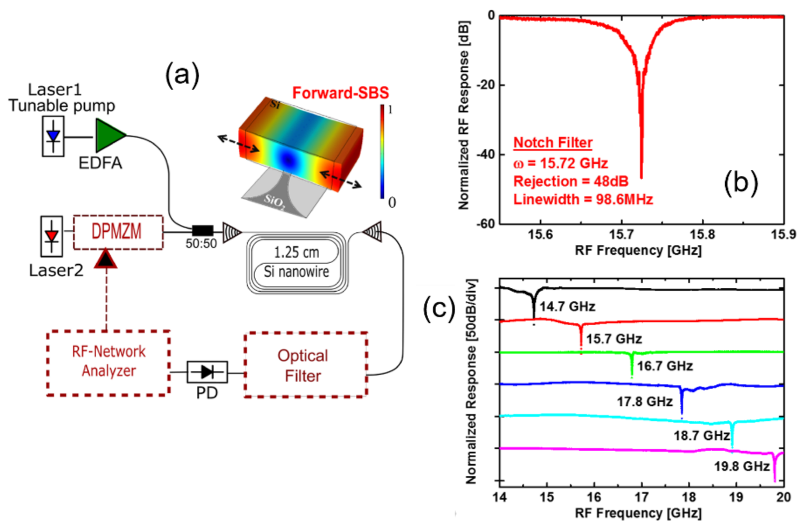

Figure 2. (a) Setup of the notch filter experiment. DPMZM, dual-parallel Mach–Zehnder modulator; PD, photodetector. The top right shows the simulated transversal acoustic displacement, or forward SBS, from a silicon nanowire. (b) Measured RF notch filter response at 15.72 GHz. (c) Filter frequency tuning where the suppression was kept above 48 dB in all measurements.

c. Long term stability enhancement of SBS notch filter [Optics Express 23, 2378 (2015)]

Microwave photonic cancellation notch filters have been shown capable of achieving ultra-high suppressions independently from the strength of optical resonant filter they use, making them an attractive candidate for on-chip signal processing. Their operation, based on destructive interference in the electrical domain, requires precise control of the phase and amplitude of the optical modulation sidebands. To date, this was attainable only through the use of dual-parallel Mach-Zehnder modulators (Figure 3a) which suffer from bias drifts that prevent stable filter operation. Here we propose a new cancellation filter topology with ease of control and enhanced stability using a bias-free phase modulator and a reconfigurable optical processor (implemented using a Fourier-Domain Optical

Processor) as the modulation sidebands spectral shaper (Figure 3b). We experimentally verify the long term stability of the novel filter topology through continuous real-time monitoring of the filter peak suppression over 24 hours (Figure 3c).

Compared to previous demonstrations, where a DPMZM was used for the sideband tailoring, the new implementation exhibited far greater stability, due to the elimination of the modulator biasing. Furthermore, the use of a Fourier-Domain Optical Processor allowed independent control over the phase and amplitude of the sidebands, greatly reducing system complexity. This enabled the realization of a simple algorithm for controlling the filter suppression, and resulted in the first demonstration of a MWP notch filter with high 40 dB suppression, over a long 24-hour period.

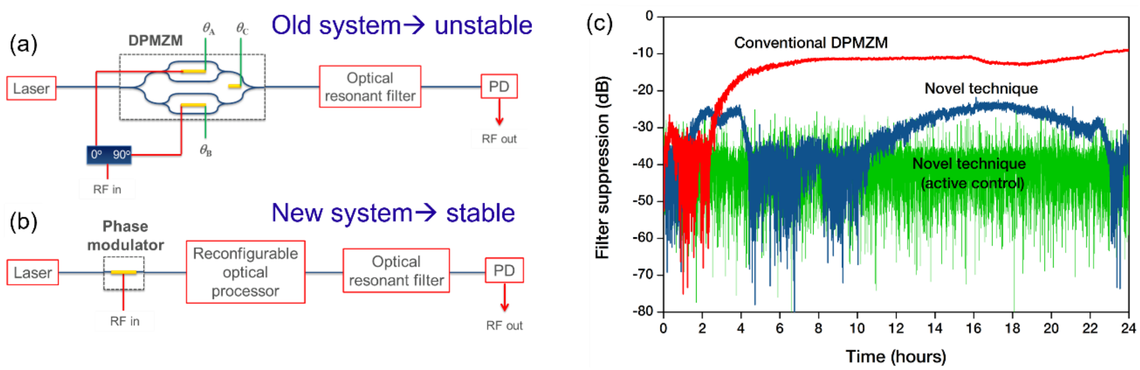

Figure 3. (a) Structure of a MWP cancellation notch filter, with DPMZM used for tailoring the sidebands' spectra. At the input of the DPMZM, an RF hybrid coupler is used to split the input RF signal between the two arms of the modulator. (b) Structure of a MWP cancellation notch filter, with a Fourier-domain optical processor (FD-OP) used for tailoring the sidebands' spectra. The enhanced functionality of the FD-OP means that the DPMZM can be replaced with a simple bias-free phase modulator. (c) Measurement of the notch filter suppression over a 24 period of continuous operation. The three plots denote different methods for tailoring the sidebands' spectra.

d. High resolution microwave frequency measurement with on-chip SBS [*Optica* 3, 30 (2016)]

The high extinction cancellation notch filter reported earlier can be implemented in an instantaneous frequency measurement system (IFM). IFM systems estimates an unknown microwave frequencies through indirect measurement, for example through power well calibrated power measurements. These systems are useful as alternatives to direct spectrum analysis, which can be heavy, complicated and limited in the frequency range.

In this work, we demonstrate experimentally a frequency measurement system that simultaneously achieves the estimation of multiple frequency measurement up to 38 GHz with errors lower than 1 MHz in a centimeter-scale chalcogenide glass waveguide. Our approach circumvents the fundamental trade-off between measurement range and accuracy. Its channelized frequency band offers an inherent capability to resolve and process multiple simultaneous RF inputs over a wide spectrum, provided the separation between multiple microwave frequencies is larger than the channel frequency spacing. The enabling technology for this breakthrough is the recently reported microwave photonic filter based on a very narrow linewidth and high extinction of SBS (Figure 4a). The results presented here point to new possibilities for creating a high-performance integrated on-chip IFM system that will help assure critical mission success at minimal costs and enhanced security for manned and/or unmanned aircraft and surface vessels and next-generation radar, with potential for monolithic integration in silicon chips.

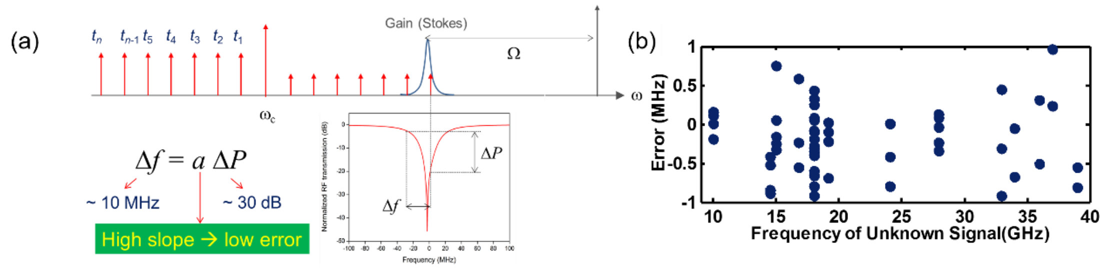

Figure 4. (a) Simplified principle of the SBS notch filter-based IFM system. The notch filter amplifies frequency changes within the notch bandwidth to a large frequency difference, essentially allowing a high slope and low frequency estimation error. (b) Measured frequency estimated errors of an RF signal in the range of 9–38 GHz; the error is less than ±1 MHz.

e. Giant Brillouin gain in a photonic chip [Journal of Lightwave Technology, accepted]

The photon-phonon interaction in SBS has been harnessed to demonstrate various on-chip functionalities such as narrowband microwave bandpass filters, notch filter, delay lines, and phase shifters. However, the performance of most of the functionalities in integrated devices have been limited by the available on-chip gain. A platform of choice for on-chip SBS is a chalcogenide, As_2S_3 and has previously exhibited a gain of up to 23 dB. For comparison tens of dBs of gain is readily achievable in kilometers of silica fiber. However, it is worth noting that the length of integrated SBS circuits is orders of magnitude lower than that of fibers, thus providing a high gain/length ratio, critical for photonic integration. In this paper, we present an optimized design and fabrication procedure for our photonic chip which resulted in an on-chip gain of up to 52 dB which is an almost 1000 times improvement over previous results. Crucially, these results were achieved through fabrication improvements led to enhanced power handling of the devices and propagation losses of 0.5 dB/cm, allowing for long propagation lengths of 13-cm and 23-cm (fabricated in the form of spirals), resulting in effective lengths of 6.5 cm and 8 cm, respectively.

The SBS gain was characterized using a high-resolution pump-probe setup. The results are shown in Figure 5, where the probe ON-OFF gain in decibels is plotted with respect to the on-chip power for the two different lengths of the waveguides (Fig. 5a). A 52 dB gain shown in Figure 4 was realized from the 23-cm at a frequency offset of 7.6 GHz (the Brillouin shift, ΩB) from the pump frequency. The 3-dB linewidth was measured to 10 MHz (Fig. 5b).

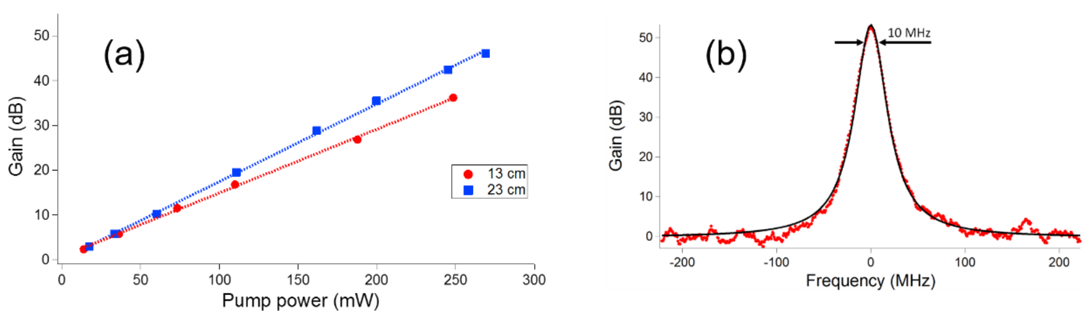

Figure 5. (a) The on-chip probe gain vs. pump power for a 23-cm and 13-cm-long chalcogenide waveguide exhibiting giant Brillouin gain. (b) The measured RF spectrum for a 23-cm-long waveguide exhibiting a gain of 52 dB. Red- experimental data, Black-Lorentzian fit.

f. Reconfigurable on-chip bandpass filter [Optics Letters 41,436 (2016)

The giant Brillouin gain in the photonic chip can be harnessed for a number of important applications that require bandwidth larger than the typical width of an SBS resonance (i.e. 30 MHz). In this work, we achieve a microwave photonic bandpass filter with a flat pass band, sharp edges, and a near rectangular shape. These features can be achieved by tailoring the SBS gain spectrum using multiple electrical lines generated from an arbitrary waveform generator (AWG) to modulate the pump using an electro-optic modulator. The giant on-chip Brillouin gain of 44 dB was harnessed to create a bandpass filter with tailored bandwidth from 30 MHz up to as high as 440 MHz (Figure 6a), which is more than an order of magnitude improvement over previous results. The filter passband ripple was maintained at <1.9 dB during operation by employing an iterative feedback loop. The central frequency of the filter was tuned up to 30 GHz, while maintaining its passband frequency response, which is a clear benefit over electronic filters (Figure 6b).

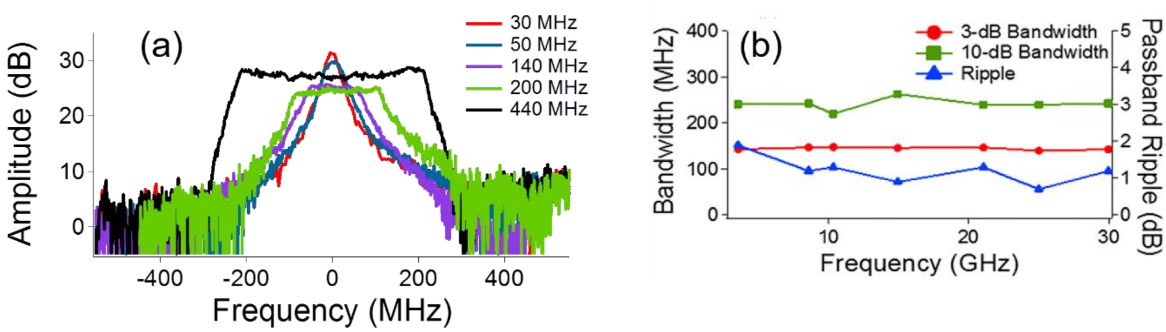

Figure 6. (a) Bandwidth reconfigurability of the MPF. By tailoring the pump, the bandwidth can be tuned from 30 MHz to 440 MHz. (b) Left axis: the 3-dB bandwidth (circle) and the 10-dB bandwidth (square) of the MPF as a function of central frequency; right axis: passband ripple of the MPF (triangle) as a function of central frequency.

g. Signal interference RF photonic bandstop filter [Optics Express 24, 14995 (2016)]

Tailoring the SBS gain can also be harnessed for creating high extinction bandstop filters. We report the microwave photonic implementation of a signal interference bandstop filter, which are filters with high extinction and wide stopbands achieved through destructive interference of two signals. We implement this concept through the combination of precise synthesis of stimulated Brillouin scattering (SBS) loss with advanced phase and amplitude tailoring of RF modulation sidebands. We achieve a square-shaped, 20-dB extinction RF photonic filter over a tunable bandwidth of up to 1 GHz with a central frequency tuning range of 16 GHz using a low SBS loss of ~3 dB. Wideband destructive interference in this novel filter leads to the decoupling of the filter suppression from its bandwidth and shape factor. The principle of operation of the filter is depicted in Figure 7a. Key to this filter is precise amplitude and phase matching over a broad bandwidth to achieve broadband cancellation. The resulting filter profile, tuned in bandwidth from 0.013 GHz to 1 GHz is shown in Figure 7b.

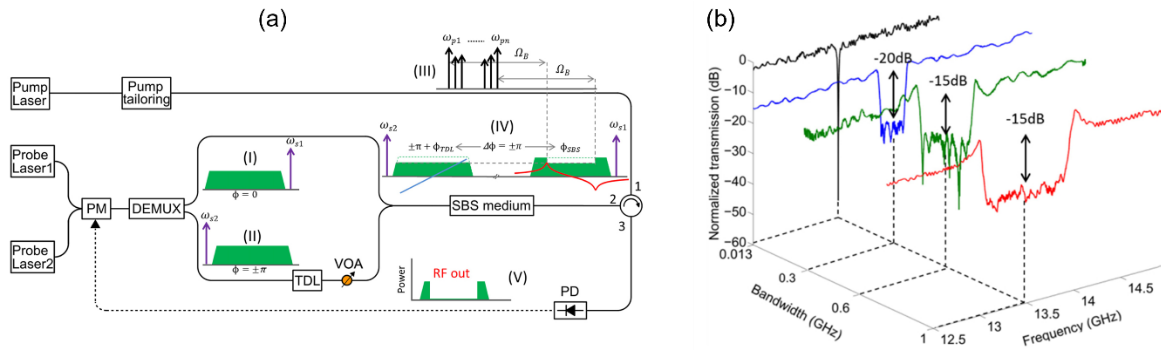

Figure 7. (a) The simplified setup and principle of operation of the reconfigurable and square-shaped bandstop MWP filter based on the signal interference technique. (I) and (II) are the phase modulated signals of two optical carriers filtered using a demultiplexer. (III) is the tailored SBS pump operating at the frequency ω_{pn} (where n is the number of the pump line) to achieve a broadened SBS profile. (IV) Amplitude matching and phase engineering of both sidebands to fulfil the cancellation condition. (V) Destructive interference of the sidebands with the corresponding carriers at the photodetector resulting in a bandstop response over the SBS profile. (b) Bandwidth reconfigurability of the bandstop filters from 0.013 to 1 GHz.

h. Lossless microwave photonic filter [Optics Letters, accepted]

We have demonstrated a new class of RF photonic filters based on frequency-selective RF interference which can decouple the filter peak suppression and bandwidth resolution Implementation of this RF interference filter using SBS led to several distinct advantages including ultra-high suppression and high resolution while maintaining a wide frequency tuning. However, these filters are based on RF signal cancellation that occurs across the whole spectrum, leading to unwanted additional loss of signals in the passband, which can degrade the filter signal-to-noise ratio (SNR) performance. In this work, we introduce a lossless and versatile RF photonic filter based on the selective RF interference technique, using the combination of an integrated silicon nitride ring resonator and SBS gain in an optical fiber (Figure 8a). The key to this breakthrough is the unique phase response of an optical ring resonator in the over-coupled (OC) regime that provides a π phase-inversion, which is necessary to achieve destructive interference and high isolation only at the intended stopband frequency. In contrast, signals are able to interfere constructively in the filter passband, providing gain for the RF signal rather than loss induced by signal cancellation.

With this technique, we experimentally demonstrate RF photonic notch and bandstop filters with no insertion loss and 1-11 GHz central frequency dynamic tuning range. The notch filter has a 60 MHz resolution and >55 dB suppression, while the bandstop filter has a nearly square stopband with >30 dB suppression, and a reconfigurable 3-dB bandwidth of 100-220 MHz (Figure 8b).

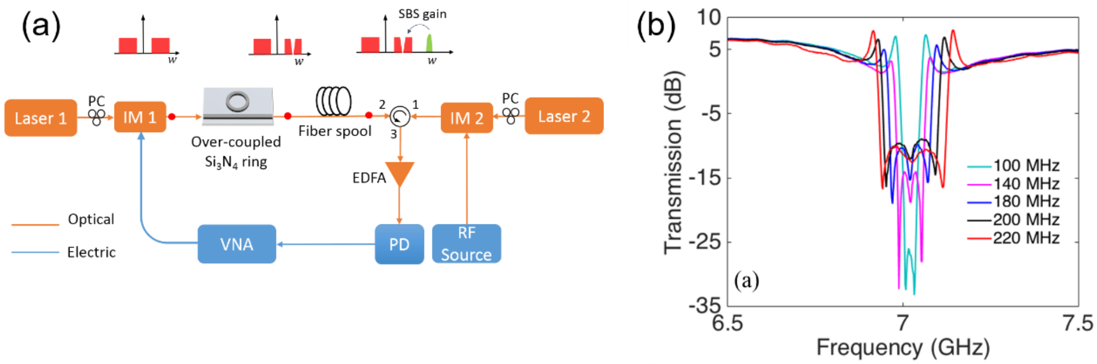

Figure 8. (a) Schematic of the experimental setup. IM, Intensity Modulator. EDFA: Erbium-Doped Fiber Amplifier. PC: Polarization Controller. PD, Photodetector. VNA: Network Analyzer. Qualitative optical spectra denoted by red points are shown above the setup diagram. (b) Measured spectra of the MWP bandstop filters with several values of 3-dB bandwidths.

i. Computer-programmable microwave photonic notch filter [hardware prototype]

A computer-controlled tunable notch filter prototype was built in this project. The photograph of the prototype is shown in Figure 9. The prototype hosted a number of components including two integrated tunable laser assemblies (ITLAs) that acted as the SBS pump and probe lasers. The maximum output power of these lasers are 15 dBm. The modulator used in the prototype is a 40 GHz phase modulator. The SBS medium used is a 1 km standard single mode fiber spooled in a small form factor. The pump and probe signal levels can be controlled using electrical and manual variable optical attenuators (VOA). A micro-EDFA is used to boost signal level prior to photo-detection. A high power-handling detector with 50 mA output current is used to low RF insertion loss can be achieved. All electrical power supplies for the lasers, EDFA, photodetector, VOA, cooling system (fan), and USB communications are hosted inside the prototype enclosure.

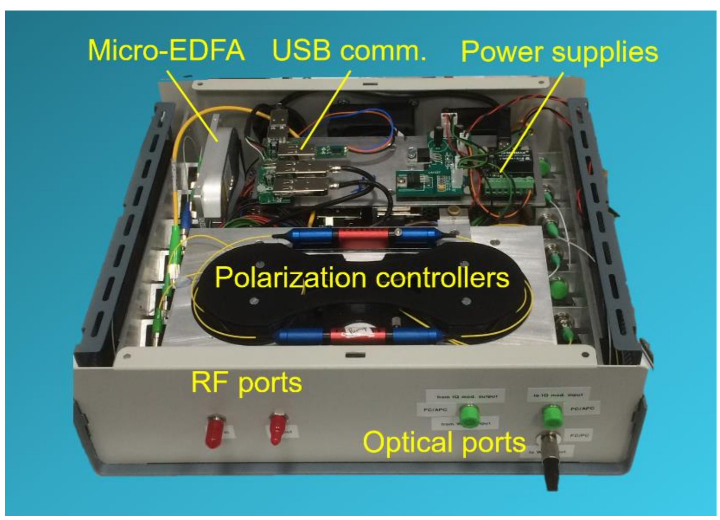

Figure 9. Photograph of the RF photonic tunable notch filter prototype created in this project, showing the components at the top of the enclosure. The prototype is hosted in an enclosure with a dimension of 28cm x 30cm x 10cm. The ITLAs, modulator, detector, and the SBS fiber medium are located at the bottom of the enclosure.

The filter can operate with two modes; namely with the internal phase modulator in conjunction with a Fourier-domain optical processor (a Finisar Waveshaper), or with an external dual-parallel Mach-Zehnder modulator (DPMZM) as outlined in the publication [Optics Express 23, 2378 (2015)]. Internal reconfiguration of the optical connections should be made to switch between these two modes of operation.
The filter can be controlled and programmed through software. The communication between the prototype and the computer is done through USBs. The control software is written in LabVIEW and the screen-shot of the graphical user interface (GUI) of this software is depicted in Figure 10.

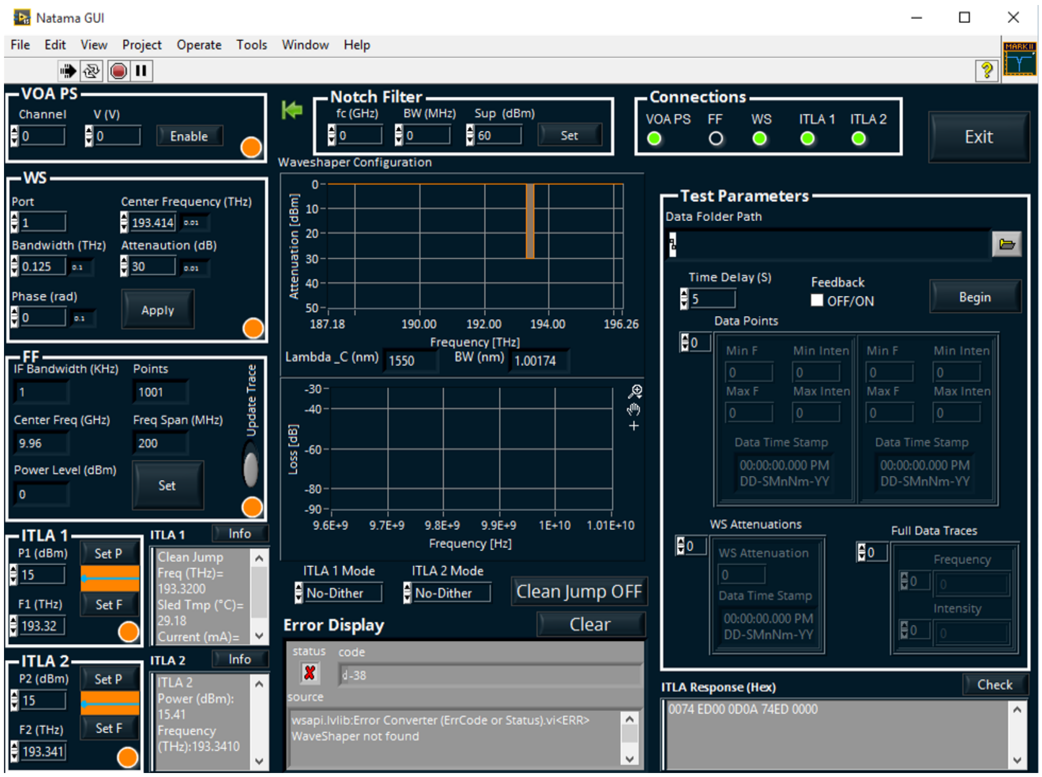

Figure 10. The graphical user interface (GUI) of the filter prototype. The software controls all critical components of the filter, including the pump and probe lasers, the Fourier-domain optical processor (Finisar Waveshaper), the VOA to control the pump power, and a network analyzer (Agilent Fieldfox) for data acquisition.

Preliminary characterizations have been carried out for the prototype. The result of notch filters with at two extreme bandwidths are shown in Figure 11. The bandwidth can be tuned from 20 MHz to 46 MHz. The typical insertion loss of the filter is -14 dB.
We characterize the long term stability of the notch frequency and suppression, in the mode of operation using the Fourier-domain optical processor. The results are shown in Figure 12. The frequency stability is of the order of 50 MHz, which is limited by the frequency noise and stability of the ITLAs. As a comparison, using external cavity laser, notch stability the order of 10 MHz can be expected. The notch suppression on the other hand can be maintained higher than 20 dB over a long period (15 hours experiment). This

suppression can be maintained at higher level if active stabilization is employed, as shown previously in [Optics Express 23, 2378 (2015)].

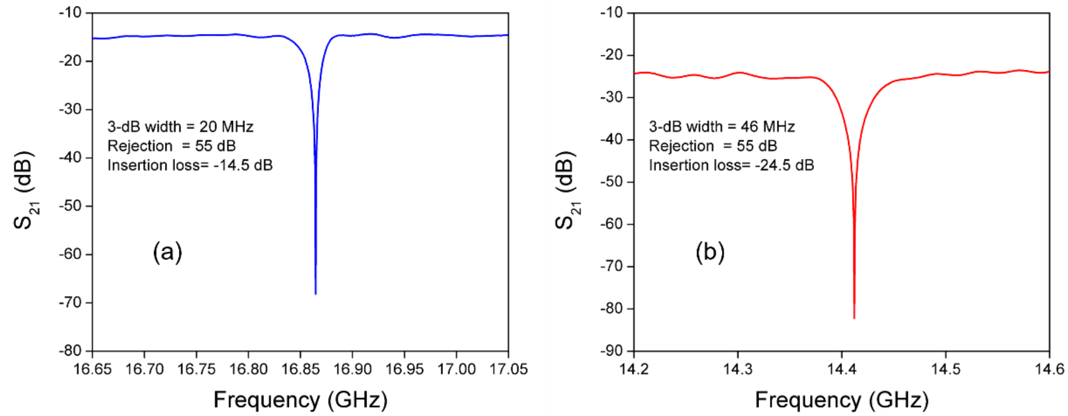

Figure 11. The RF transmission of the notch filter measured using vector network analyzer. (a) A notch formed using 7.8 dB of SBS gain, exhibiting 55 dB rejection, -14.5 dB insertion loss, and a highest resolution of 20 MHz. (b) A notch formed using 7.7 dB of SBS loss, exhibiting 55 dB of rejection, -24.5 dB insertion loss and a resolution of 46 MHz.

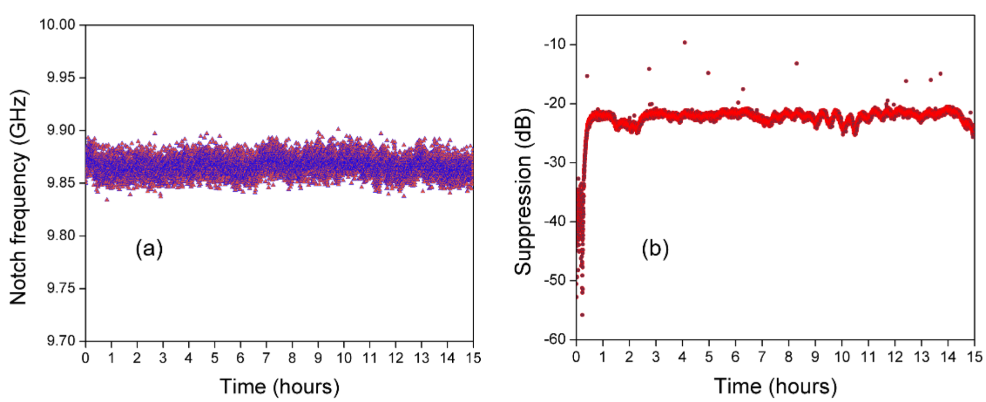

Figure 12. Long term stability of the notch filter prototype. (a) Notch frequency stability is of the order of 50 MHz. (b) The suppression can be maintained above 20 dB over 16 hours period without any active stabilization.

The specifications of the prototype are summarized in the table below:

Specification	Value
Dimension	L= 28 cm, W = 30 cm, H = 10 cm
Central frequency tuning	0.5-20 GHz
Rejection	55 dB (max), 20 dB (typical)
3-dB width	20-46 MHz (continuously tunable)
Passband insertion loss	-14 dB (min)
Frequency stability	50 MHz
RF connectors	2.92 mm female
Optical connectors	2 x FC/APC; 1x FC/PC
Supply	220 V
Communications	USB
Software operation	LabVIEW

Currently there is an on-gong plan to commercialize this unique tunable filter technology through CUDOS startup Luxava Technologies. In the coming months demonstrations of the filter are planned for research laboratories and defense organization in Australia, as well as exhibiting in major optical and microwave conferences (IMS, CLEO, IEEE MWP).

Published journal papers with AOARD acknowledgement

1. A. Choudhary, B. Morrison, I. Aryanfar, S. Shahnia, M. Pagani, Y. Liu, K. Vu, S. J. Madden, D. Marpaung, and B. J. Eggleton "Advanced integrated microwave photonic signal processing with giant on-chip Brillouin gain", ***Journal of Lightwave Technology*** (accepted, 2016) **[invited paper]**
2. Y. Liu, D. Marpaung, A. Choudhary, and B. J. Eggleton "A lossless and high resolution RF photonic filter", ***Optics Letters*** (accepted, 2016)
3. I. Aryanfar, A. Choudhary, S. Shahnia, M. Pagani, Y. Liu, K. Vu, S. J. Madden, B. Luther-Davies, D. Marpaung, and B. J. Eggleton "Signal interference RF photonic bandstop filter", ***Optics Express*** 24, 14995 (2016)
4. H. Y. Jiang, D. Marpaung, M. Pagani, K. Vhu, D.Y. Choi, S. Madden, L. S. Yan, and B. J. Eggleton, " High resolution, multiple frequencies microwave measurement using an on chip tunable Brillouin RF photonic filter", ***Optica*** 3, 30 (2016)
5. A. Choudhary, I. Aryanfar, S. Shahnia, B. Morrison, K. Vu, S. Madden, B. Luther Davies, D. Marpaung, and B. J. Eggleton, " Tailoring of the Brillouin gain for on-chip widely tunable and reconfigurable broadband microwave photonic filters", ***Optics Letters*** 41,436 (2016)
6. S. Shania, M. Pagani, B. Morrison, B. J. Eggleton, and D. Marpaung, " Independent manipulation of the phase and amplitude of optical sidebands in a highly-stable RF photonic filter", ***Optics Express*** 23, 2378 (2015)
7. A. Casas-Bedoya, B. Morrison, M. Pagani, D. Marpaung, and B. J. Eggleton, " Tunable narrowband microwave photonic filter created by stimulated Brillouin scattering from a Silicon nanowire", ***Optics Letters*** 40, 4154 (2015)
8. D. Marpaung, B. Morrison, M. Pagani, D.-Y. Choi, B. Luther-Davies, S.J. Madden, and B.J. Eggleton, "Low power, chip-based stimulated Brillouin scattering microwave photonic filter with ultrahigh selectivity," ***Optica*** 2, 76 (2015).

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9. M. Merklein, A. Casas-Bedoya, D. Marpaung, T.F.S. Buettner, M. Pagani, B. Morrison, I.V. Kabakova, and B. J. Eggleton, " Stimulated Brillouin scattering in photonic integrated circuits: novel applications and devices", ***IEEE Journal of Selected Topics in Quantum Electronics*** (2016) **[invited paper]**
10. B. Morrison, Y. Zhang, M. Pagani, B. J. Eggleton, and D. Marpaung "Four wave mixing and nonlinear losses in thick silicon waveguides", ***Optics Letters*** 41,2418 (2016)
11. M. Pagani, , B. Morrison, Y. Zhang, A.Casas-Bedoya, T. Aalto, M. Harjanne, M. Kapulainen, B. J. Eggleton, and D. Marpaung, " Low-error and broadband microwave frequency measurement in a silicon chip", ***Optica*** 2, 751 (2015)
12. M. Pagani, D. D. Marpaung-Y. Choi, S.J. Madden, B. Luther-Davies, and B.J. Eggleton, "Tunable wideband microwave photonic phase shifter using on-chip stimulated Brillouin scattering," ***Optics Express*** 22,28810 (2014)

13. D. Marpaung, M. Pagani, B. Morrison, and B.J. Eggleton, "Nonlinear integrated microwave photonics", ***Journal of Lightwave Technology*** 32,3421 (2014) **[invited paper]**
14. D. Marpaung, M. Pagani, B. Morrison, R. Pant, and B.J. Eggleton "Ultra-high suppression microwave photonic bandstop filters", ***Chinese Science Bulletin*** 59, 2684 (2014) **[invited paper]**
15. R. Pant, D. Marpaung, I.V. Kabakova, B. Morrison, C.G. Poulton, and B. J. Eggleton "On chip stimulated Brillouin Scattering for microwave signal processing and generation", ***Laser and Photonics Reviews*** 8, 653 (2014) **[invited paper]**

Conference paper/poster/presentation funded by AOARD grant

1. Choudhary, A., Aryanfar, I., Shahnia, S., Morrison, B., Vu, K., Madden, S., Luther-Davies, B., D. Marpaung, Eggleton, B. (2016). On-chip tunable microwave photonic filters with a reconfigurable bandwidth of up to 440 MHz. ***Optical Fiber Communication Conference*** 2016, Anaheim.
2. A. Choudhary, I. Aryanfar, S. Shahnia, B. Morrison, K. Vu, S. Madden, B. Luther-Davies, D. Marpaung, B. J. Eggleton, "On-chip broadband RF photonic filters using giant Brillouin gain," ***ANZCOP***, Adelaide, Australia, 2015 [postdeadline paper]
3. Pagani, M., Shahnia, S., Morrison, B., Eggleton, B., D. Marpaung (2015). Highly-stable RF photonic cancellation filter. ***2015 IEEE International Topical Meeting on Microwave Photonics*** (MWP 2015), USA.
4. Jiang, H., D. Marpaung, Pagani, M., Yan, L., Eggleton, B. (2015). Multiple frequencies microwave measurement using a tunable Brillouin RF photonic filter. ***11th Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR 2015),*** Washington DC: OSA (Optical Society America).
5. Casas Bedoya, A., Morrison, B., Pagani, M., D. Marpaung, Eggleton, B. (2015). CMOS-compatible RF notch filter enabled by SBS in silicon. ***Nonlinear Optics (NLO 2015)***, Kauai: OSA (Optical Society America). **[postdeadline paper]**
6. Casas Bedoya, A., Morrison, B., Pagani, M., D. Marpaung, Eggleton, B. (2015). Ultra-narrowband tunable microwave filter created by stimulated Brillouin scattering in a Silicon chip. **Frontiers in Optics 2015**: The 99th OSA Annual Meeting and Exhibit/Laser Science XXXI, Washington: The Optical Society.

Invited talks

1. B. Eggleton ***Asia Communications and Photonic Conference***, "Stimulated Brillouin Scattering in Photonic Integrated Circuits for Signal Processing," November 2016, Wuhan, China.
2. B. Eggleton, **IEEE Photonics Conference 2016**, "Harnessing photon-phonon interactions in circuits", October 2016, Hawaii, USA
3. B. Eggleton, ***SPIE Photonics West***, "Enhancing and inhibiting stimulated Brillouin scattering on photonic integrated circuits" [9371-10], 9 February 2015, San Francisco, USA.
4. B. Eggleton, ***Nonlinear Optics (NLO),*** "Enhancing and Inhibiting Stimulated Brillouin Scattering in Photonic Integrated Circuits" [NF1A.1], 31 July 2015, Kauai, USA.

5. B. Eggleton, ***10th International Symposium on Modern Optics and Its Applications (ISMOA) 2015***, “Stimulated Brillouin Scattering in Photonics Integrated circuits: 11 August 2015, Bandung, Indonesia.
6. D. Marpaung, ***Optical Fiber Communication Conference and Exposition (OFC) 2016***, 20-24 March 2016
7. D. Marpaung, ***European conference on optical communications (ECOC).*** “Integrated microwave photonics”, 27 Sept 2015
8. D. Marpaung, ***CLEO Pacific Rim 2015***, “Material platforms for integrated microwave photonics”, 24 August 2015
9. D. Marpaung, ***Integrated photonic research symposium (IPR 2015),*** “Energy efficient RF photonic signal processing with on-chip SBS”, 27 June 2015

Received additional fund for your research efforts related to AOARD grant

1. Stimulated Brillouin Scattering in semiconductor devices, AUD 552,000, 2016-2018
2. Smart radio-frequency filter in a tuneable optical circuit, AUD 357,000, 2015-2017
3. Ultra-portable and Programmable Microwave Photonic Filter, AUD 35,000, 2015-2016

IP disclosure/Patent/Patent submitted (title, date submitted):

1. D. Marpaung, M. Pagani and S. Shahnia, "High stability microwave photonic notch filter," Provisional patent, CDIP Ref. #2015-035-PRO-0 (2015)

Visited AFRL/DoD installation in US, including under AOARD WoS program

1. US Army Research Laboratory, Adelphi, MD, 28 October 2015 (Dr. A. Casas Bedoya)
2. DARPA, Arlington,VA, 2015 (B. Eggleton)
3. US Army Research Laboratory, Adelphi, MD, 2015 (B. Eggleton)
4. DARPA Arlington, VA, February 2016 (B. Eggleton)
5. NRL, Washington DC, February 2016 (B. Eggleton)
6. US Army Research Laboratory, Adelphi, MD, February 2016 (B. Eggleton)

Collaborations

1. ARL: Dr. Weimin Zhou, CRADA, Technical data exchange on silicon photonics
2. AFRL Materials Directorate: Dr. Rob Nelson
3. AFRL Sensors Directorate: Dr. Nick Useshak
4. AFRL AFOSR: Dr. Gernot Pomrenke on CSP support on Workshop on Optomechanics and Brillouin Scattering (WOMBAT 2015)
5. NRL: Dr. Craig Hoffman and his group
6. NRL: Dr. Jason McKinney
7. NRL: Dr. Keith Williams.
8. Stanford University: Prof. Shanhui Fan
9. University of Michigan: Prof. Herbert Winful
10. University of Massachusetts at Boston: Prof. Richard Soref
11. ORC Southampton: Prof. Graham Reed and Prof. Anna Peacock
12. Macquarie University: Prof. Mike Steel
13. Ghent University and IMEC: Prof. Roel Baets
14. University Technology Sydney: A/Prof. Chris Poulton
15. Australian National University: A/Prof. Steve Madden